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1995 Test of the Vector Slope Gauge at Duck, North Carolina

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Abstract

We performed a successful experiment to verify performance of the revised Vector Slope Gauge (VSG) and Ku-band scatterometer. We made measurements of the two orthogonal components of the ocean surface slope at Duck Pier during the second week of December 1995 with the VSG. The radar backscatter measurements at Ka band (VSG) and Ku band were of the same area on the ocean surface. Using the VSG-measured slopes, we determine the primary wave direction, power-slope modulation, and an estimate of the wind speed. Our measurements show strong agreement to the US Army Field Research Facility's (FRF) comparable measurements of waveheight, wave period, wind speed, and wave direction. Our new Autoregressive (AR) technique examines individual cycles of the primary wave. The powerful AR method allows us to see the non-linearities associated with each wave cycle instead of the traditional frequency dissecting when using the modulation transfer function (MTF). The AR method does not have any restriction to the primary wave direction. We illustrate the usefulness of the VSG by applying the AR technique to the VSG slope measurement.

The experiment at Duck Pier proved the slope-measuring concept of the VSG. We believe the unique VSG surface slope measurement, in conjunction with the AR technique, will result in new insights into ocean modeling for better interpretation of SAR images. We also believe the VSG will be an important tool for oceanographers as a wave-direction finder and tool for slope measurements. To reap the full scientific potential of the proven, fully operational VSG, we need to conduct a tower experiment in the open ocean with other participants. We are excited by the Duck Pier results and look forward to using the proven VSG in the full open-ocean environment.

I. The 1995 Test of the Vector Slope Gauge at Duck, NC

a) Introduction

Our successful experiment at Duck Pier verified the performance of the revised Vector Slope Gauge (VSG) and Ku-band scatterometer. The Ka-band VSG and Ku-band scatterometer measured radar backscatter from the same area on the ocean surface. As a result of the VSG's measured surface slopes we were able to determine the primary wave direction, power-slope modulation, and an estimate of the wind speed. The US Army Field Research Facility's (FRF) measurements show strong agreement to our comparable measurements of waveheight, wave period, wind speed, and wave direction. We used both the standard spectral methods and the AR technique to analyze the data. The AR method provides new insights into the relations between waveheight, radar signals, and wave slopes. The experiment at Duck Pier proved the slope-measuring concept of the VSG.

The VSG measures the two orthogonal components of the ocean surface slope. It is a 35-GHz range-measuring radar scatterometer with a three-beam antenna. At the Duck Pier experiment the three beams were switched sequentially at 1/300-s intervals to illuminate three adjacent spots of the ocean surface. The VSG measures the range to each of the three footprints, which allows determination of the average surface elevation for each footprint and a first-order approximation of the two-dimensional ocean wave slope.

The modulation of microwave cross section by the large-scale ocean waves is due to two effects: (1) the tilt modulation and (2) the hydrodynamic-aerodynamic modulation. Tilt (slope) modulation is a purely geometric effect because ripples are seen by the radar at different local angles of incidence depending on their location on the long wave. Passing large-scale waves tilt the surface upon which the ripples reside, producing a new local angle of incidence, modifying the Bragg resonance wavelength. Hydrodynamic modulation is due to interactions between ripples and large-scale waves, resulting in a nonuniform distribution of the small-scale ripples of a given wavelength over the large scale wave [Keller and Wright, 1975; Alpers and Hasselmann, 1978; Phillips, 1981]. Aerodynamic effects, associated with wind turbulence driven by the large-scale waves, may also contribute to hydrodynamic modulation of ripples. The amplitude of the Bragg ripple changes due to interactions between short and long waves, the hydrodynamic modulation. This change affects the strength of the backscattered signal. Since the radar only *sees* the Bragg ripples, the long waves are imaged through their modulation of the short ripples and the underlying slopes. The conversion of microwave scattering cross sections to wave parameters requires information about how large-scale waves affect Bragg ripples.

The linear model described by Wright, et al. [1980], Plant [1991], Alpers, et al. [1981] is often used to describe the modulation for low-to-moderate sea states. By using the MTF, the model assumes linear dependence between the microwave backscattered power and

the long-ocean-wave height or its slope or, alternatively, the horizontal component of the orbital velocity. The transfer functions based on this model contain both tilt (or slope) and hydrodynamic-aerodynamic modulation.

Numerous investigations to measure the MTF have been conducted in recent years. The investigations involved measurements of the radar return signal strength and simultaneous measurements either of Doppler frequency shift of the radar signal or waveheight in the radar beam. A major shortcoming of these investigations is the dependence on point measurements of height or Doppler. Point height and Doppler measurements may be converted to slope if one assumes long-crested waves, with no slopes parallel to the crests, and also if linearity assumptions are valid. The actual slope modulation of the signal, however, depends on the vector slope, which also has components normal to the direction of wave travel.

The VSG bypasses the need of making the conventional assumptions associated with the MTF by actually measuring the vector slope and return signal strength simultaneously. With our instantaneous measurements of slope and backscattered signal, we may find the slope (or tilt) modulation. From our measurements of the backscattered signal, we know the overall radar-signal modulation. Using the VSG we know directly the slope (or tilt) modulation and the overall radar-signal modulation; therefore, we may remove the known contribution of the tilt modulation from the known overall radar-signal modulation and obtain an estimate of the hydrodynamic modulation.

During our experiment at Duck Pier, we made measurements of the vector slope and the backscattered signal. These measurements allow us to find the tilt modulation and estimate the hydrodynamic modulation. The VSG performed excellently by measuring the proper vector slope and the backscattered signal. Comparison of our measurements with similar FRF measurements shows strong agreement. Having measured the vector slope, we are preparing several papers based on the Duck Pier experimental results for submission to refereed journals. The short Duck Pier experiment sufficed to prove our slope measuring concept; however, we need to conduct an open-sea tower experiment to realize the full potential of the VSG. We believe an open-sea experiment will further the understanding of modulation of radar signals by ocean waves that is important for improving satellite synthetic aperture radar (SAR) operation for global ocean study. Moreover, near-shore measurements can lead to better understanding of the imaging of the ocean in and near the surf zone.

b) Experimental Description

The University of Kansas Radar Systems and Remote Sensing Laboratory made radar backscatter measurements from the ocean surface at the US Army Field Research Facility's (FRF) Pier in Duck, North Carolina, during the second week of December 1995. Graduate students Justin Legarsky and Louis Brown conducted the field experiment at Duck Pier.

We mounted the Ka-band VSG and Ku-band scatterometer on the pier rail at 580 m from the shore and we set the radar look direction at 160° East of True North (looking southward longshore) at an angle of incidence of 61° measured from nadir. A small empty nearby shed that was available on the pier served as our remote operations room for housing the control unit and data-acquisition system. We observed the weather to be cloudy but saw no rain during our recorded measurements. FRF's anemometer made measurements of the average wind speed every 34 minutes (for our recorded measurement the wind speed varied from 4 m/s to 9 m/s). We made a logbook of visual observations (including several photographs of the surface) of the primary wave period and primary wave direction during the time we recorded measurements. For an estimate of surface truth, we chose the two nearby FRF instruments, gauge 3932 — an anemometer located 5 meters from the radar setup and gauge 625 — a Baylor Staff

located 12 m from the radar setup. They served as the main comparison to our measurements of waveheight, wave period, and wind speed estimate.

To aid in fine tuning the VSG and Ku-band systems on the pier, we observed the radar return spectra on a Hewlett-Packard spectrum analyzer. We estimated the signal-to-noise ratio by pointing both radars toward the sky to determine the noise floor. Additionally, we observed the real-time analog signals proportional to the received radar power and to the slant range to the ocean surface on an oscilloscope and noted that the radars were fully functional [Legarsky, 1995]. We observed the signals proportional to the waveheight from the Ku band and VSG together. They showed strong visual agreement as expected, since the Ku-band footprint and the VSG footprints cover the same area. We found to be fully operational the new faster data acquisition system that allows the instantaneous 2-D ocean surface slope measurement every 10 ms. We simultaneously monitored the data signals from the three beams of the VSG to ensure

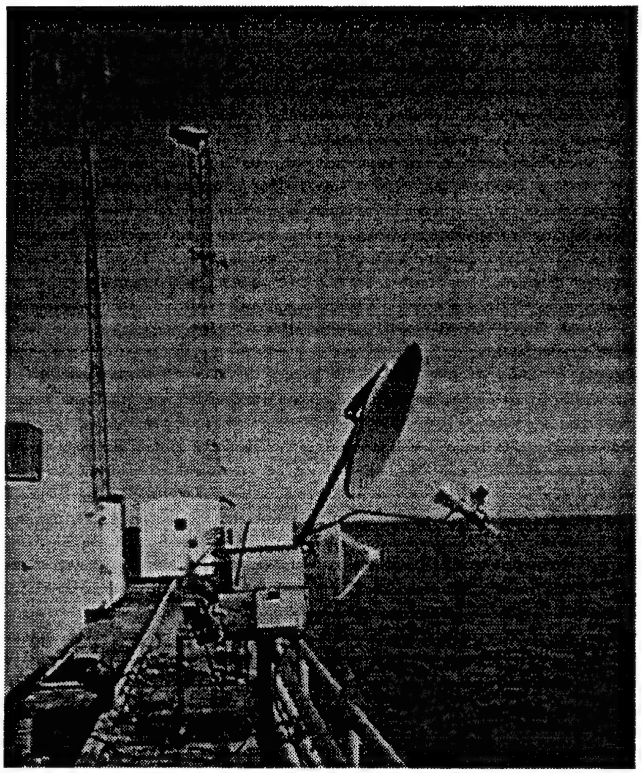


Figure 1. VSG and Ku-Band setup at Duck Pier.

proper operation. We did this using a new addition, a trigger output signal from our new faster data-acquisition system, with an oscilloscope display.

Having tuned the radar systems for the Duck pier experimental scene, we measured the

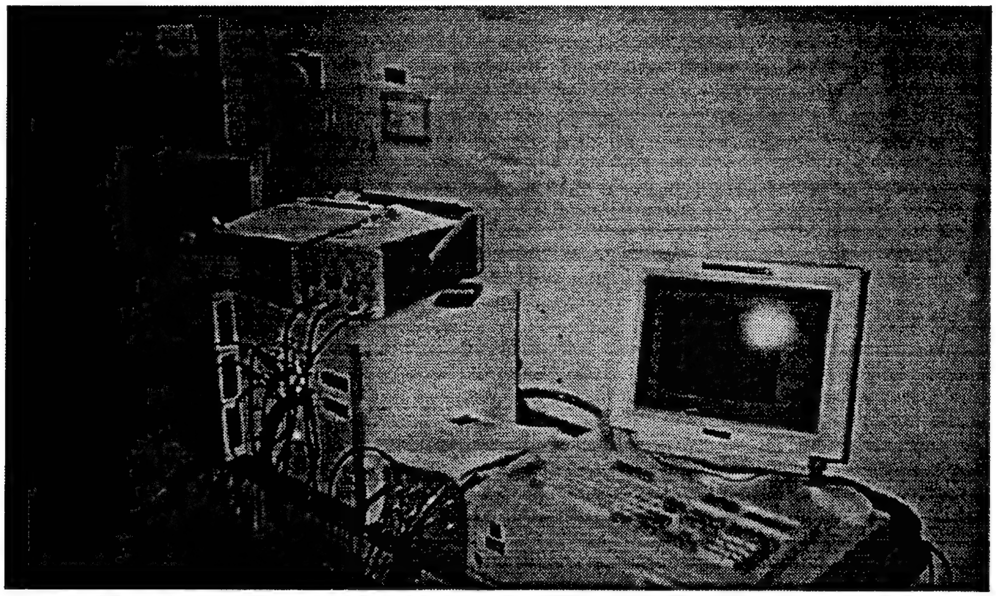
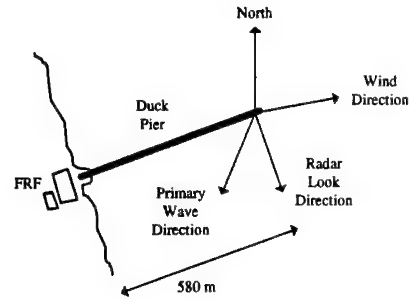


Figure 2. Inside of operations control room.

ocean surface for two days. From our measurements, we computed the waveheight, the differential scattering coefficient, and the instantaneous 2-D surface slope by using post-processing algorithms developed at The University of Kansas (KU).



II. Experimental Results

a) Vector Slope Gauge and Ku-band — MTF comparison

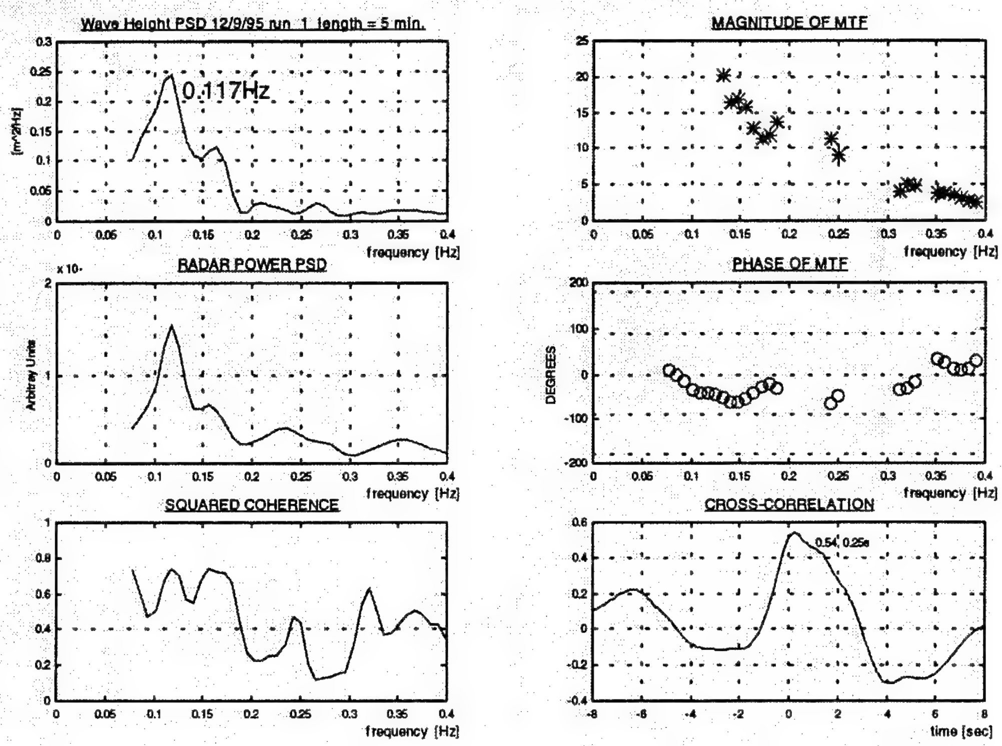


Figure 3. ***Ku-band*** **MTF.**
data file run_1 collected on 12/09/95. Angle of incidence is 61°. Wind Speed is 4.5 m/s.
Wind Direction is 258°. Primary Wave Direction is 29°. Radar Look Direction is 160°. Polarization is HH.

We computed the modulation transfer function (MTF), return-power and waveheight power spectral densities, coherence function, and cross correlation for both the VSG and Ku-band system.

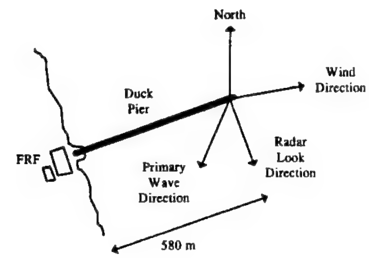
$$M(f) = \frac{G_{pw}(f)}{\bar{p} \cdot K \cdot G_{ww}(f)}$$

$$\gamma^2 = \frac{\left|G_{pw}(f)\right|^2}{G_{pp}(f) \cdot G_{ww}(f)}$$

where,
- $M(f)$ is the modulation transfer function
- $G_{pw}(f)$ is the cross spectrum of the backscattered power and long wave height
- $G_{ww}(f)$ is the autospectrum of wave height
- $G_{pp}(f)$ is the autospectrum of the backscattered power
- $\bar{p}$ is the mean received power
- γ^2 is the coherence function

We see strong agreement in our two independent system measurements of waveheight and return power from run_1 shown in figures 3 & 4. Maximum waveheight and return

power energy occur at 0.117 Hz (8.5-s wave period) for both of our instruments. Interestingly, the MTF phase at the primary wave frequency, 0.117 Hz, for the Ku band and VSG differs by 20°. On the MTF phase plot zero corresponds to the wave crest, plus phases correspond to the front face of the wave, and minus phases correspond to



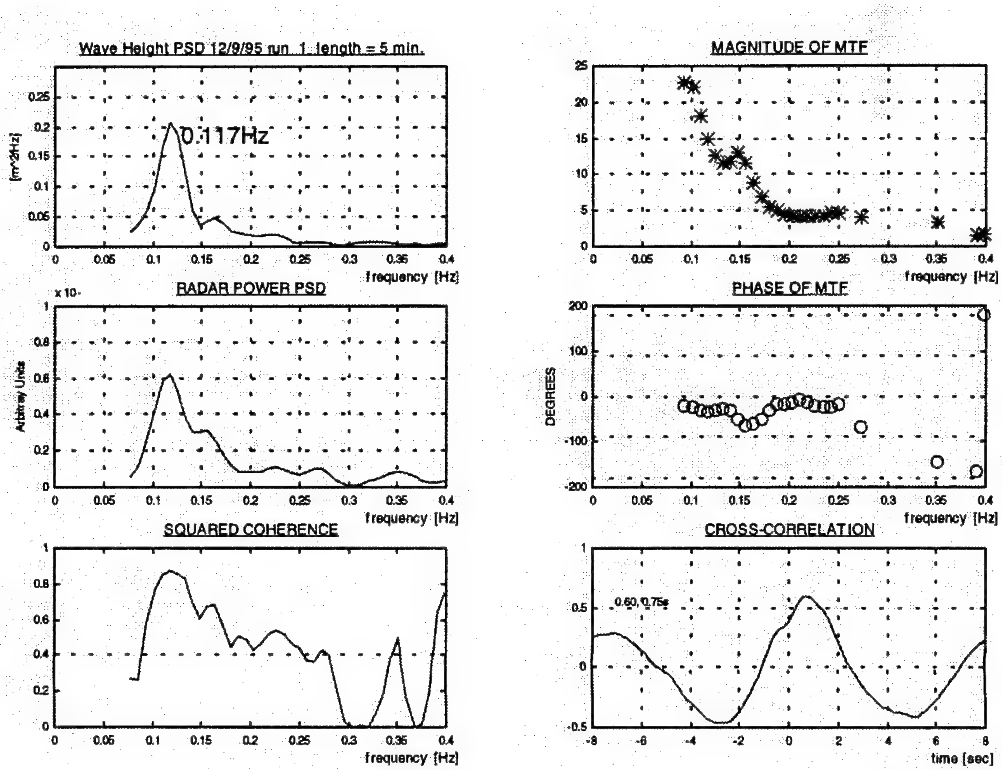


Figure 4. ***VSG Ka-band*** **MTF.**

data file run_1 collected on 12/09/95. Incidence angle is 61°. Wind Speed is 4.5 m/s.
Wind Direction is 258°. Primary Wave Direction is 29°. Radar Look Direction is 160°. Polarization is VV.

the back face of the wave (note: we are looking at the back of the long wave since the wave direction is about midway between downwave and crosswave). Both the Ku band and the VSG MTF phases (50° and 30°, respectively) position the maximum power return at the back face of the wave. We believe the fact that the two independent systems, Ku band and VSG, measuring the same ocean surface patch give highly correlated results proves that both systems are making the proper relative measurements.

b) Agreement Between Our Measurements and FRF Measurements

b.1) *Waveheight*

We show a three-hour data set comparison of our waveheight measurements compared to the FRF waveheight measurements in figure 5. Our mean value of significant waveheight

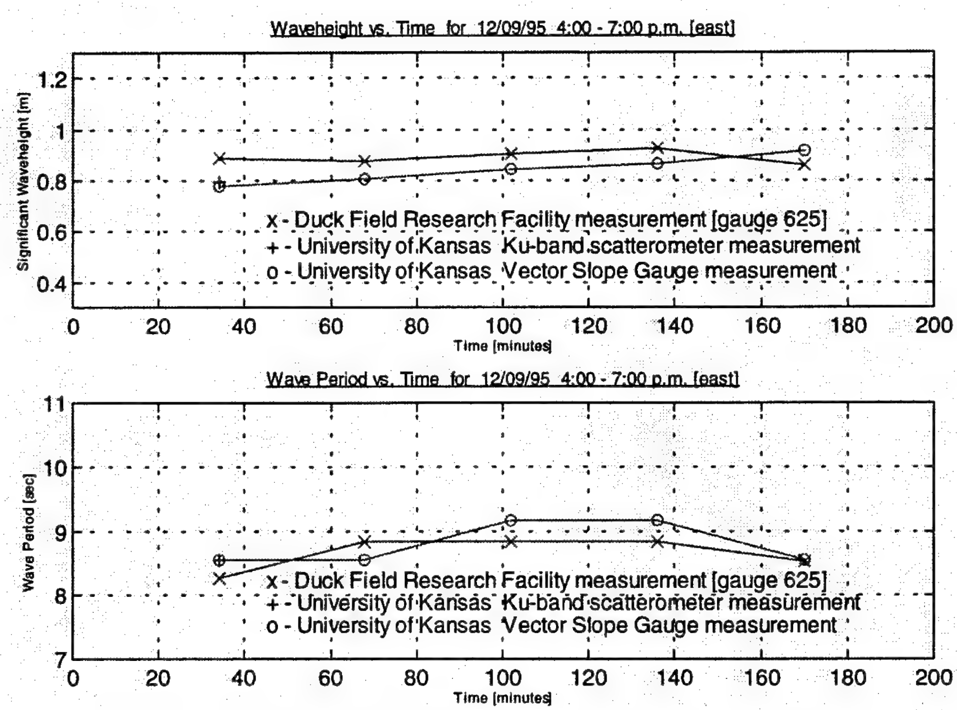


Figure 5. Wave Height and Wave Period measurement comparison.

(hmo) computes to 0.84 m, which is within 6 percent of the FRF hmo, 0.89 m. Our two measurements (Ku and Ka bands) of hmo are nearly identical, and we believe the FRF 6 percent difference arises from non-identical measurement location and by the way the Baylor Staff makes the measurement.

b.2) *Wave Period*

Our mean wave period measurement shows good agreement over the three-hour data set shown in figure 5, and our measured mean wave period is within 2 percent of the FRF measurement. We believe the small 2 percent difference is due to the fact we determine the wave period from the highest energy peak of our spectral analysis instead of integrating over a band of frequencies as FRF does.

b.3) *Wind Speed*

We estimate the wind speed, u, from the VSG 2-D slope measurement by using the classical optical data of Cox and Munk [1954,1956] that give a linear wind speed dependence for the mean-square slope: $s^2 \cong \alpha \cdot u$. Many authors since Cox and Munk

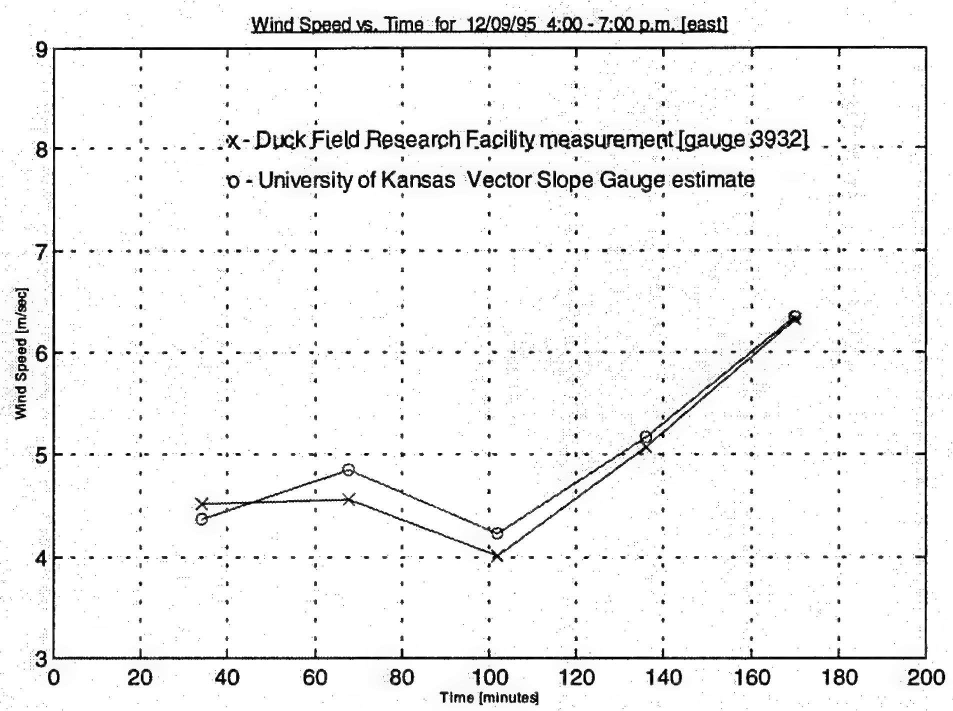


Figure 6. Wind speed comparison.

have estimated the proportionality factor, α. We use the proportionality factor of 0.004 [Apel, 1994] that is quite robust across all wind speeds, frequencies, and incidence angles for which data are available. By using our slope measurement, we calculate the mean-square slope and divide it by the proportionality factor of 0.004 to obtain the wind speed estimate: $u_{est} = \dfrac{s^2}{0.004}$, where u_{est} is the estimated wind speed in m/s and s^2 is the measured mean-square slope.

From our slope measurement we obtain a wind speed estimate that is within 2 percent of the FRF anemometer measurement. Our mean-square-slope measurement strongly agrees with the empirical relation of Cox and Munk that has been field tested and confirmed by many other authors over the last 40 years.

b.4) ***Wave Direction***

Using the VSG measurement of the two orthogonal components of the ocean surface slope we estimated the primary wave direction. We compute the wave-direction axis as the rotation from true North of the major axis of an ellipse that fits the slope components.

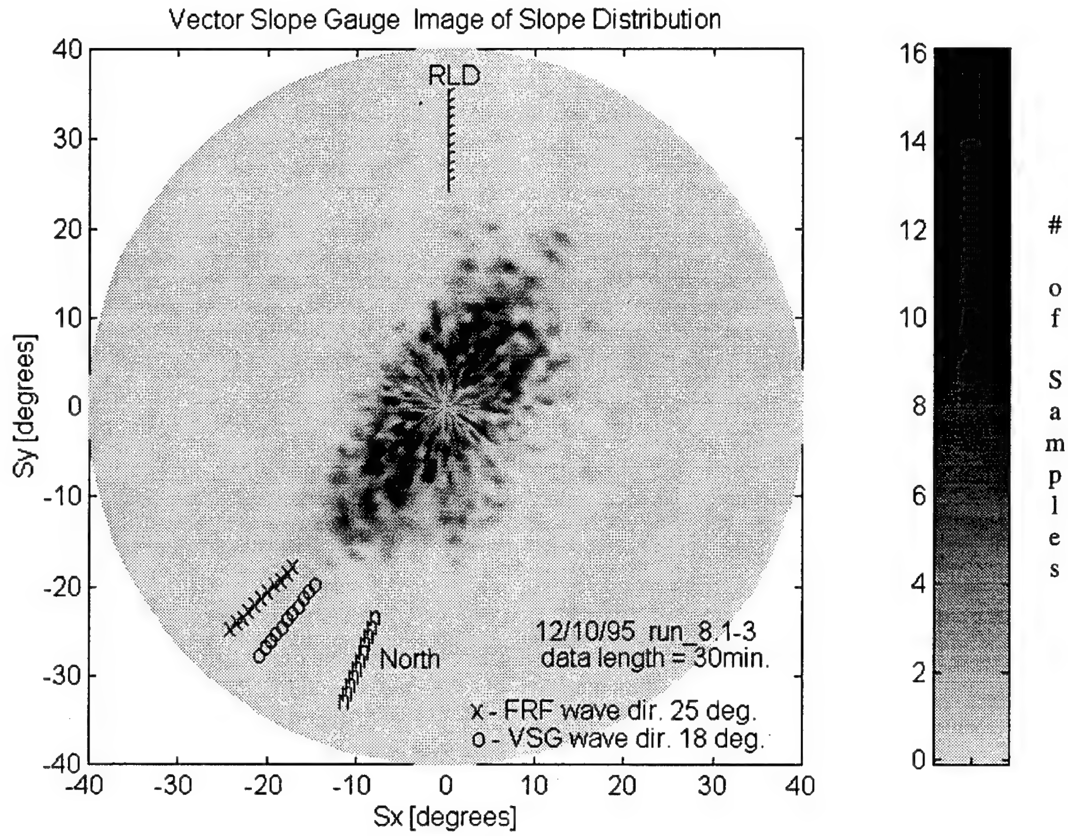


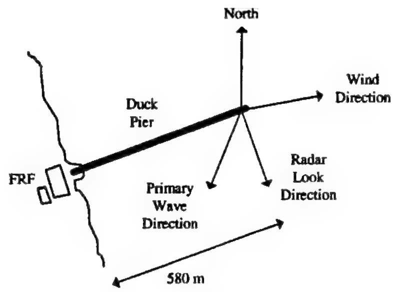
Figure 7. Primary-wave direction determined from VSG slope measurement.

Since the slope measurement is a time series, we assume that more slopes exist on the back face of the primary wave; therefore, we resolve the primary axis ambiguity to measure the primary wave direction.

Our wave-direction measurement (figure 7) shows strong agreement (within 7°) to FRF's measurement. We believe our wave direction measurement to be superior to the FRF due to our highly detailed surface profile measurement made possible by the instantaneous surface slope measurement every 10 ms.

c) Power-Slope Modulation

c.1) *VSG Slope MTF*



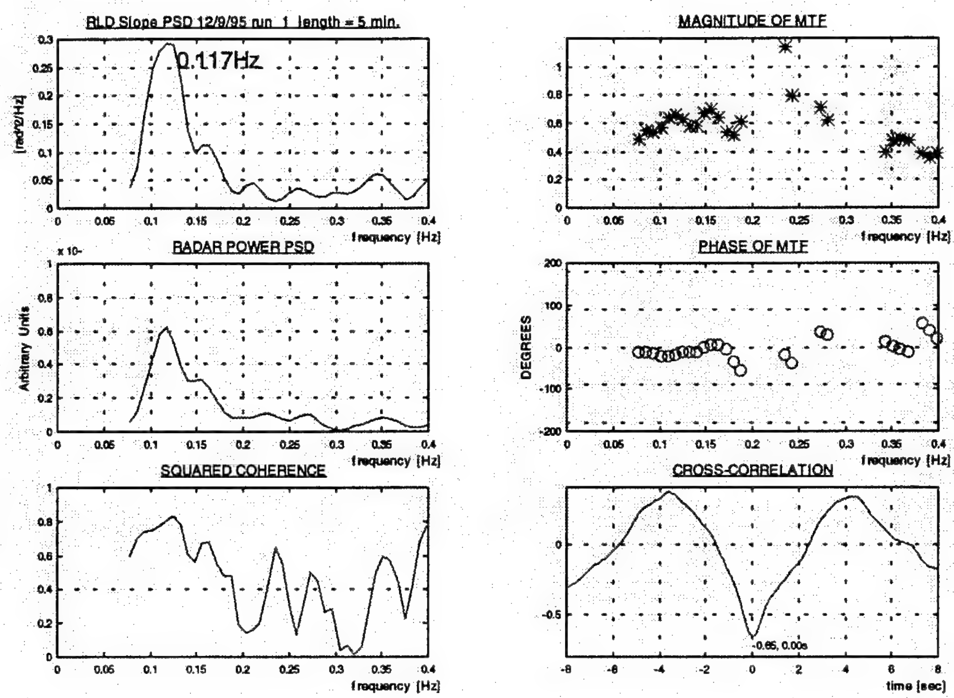


Figure 8. Vector Slope Gauge MTF.
data file run_1 collected on 12/09/95. Incidence angle is 61°. Wind Speed is 4.5 m/s. Wind Direction is 258°. Primary Wave Direction is 29°. Radar Look Direction is 160°. Polarization is VV.

We derive a slope modulation transfer function by assuming that the relation between radar backscattered power and the long-wave slope is linear and can be described by the transfer function *M(f)*. The MTF, in terms of slope, is then given by

$$M(f) = \frac{G_{ps}(f)}{\overline{p} \cdot G_{ss}(f)}$$

where,
M(f) is the slope modulation transfer function
G_{ps}(f) is the cross spectrum of the backscattered power and the long-wave slope
G_{ss}(f) is the autospectrum of slope
$\overline{p}$ is the mean received power

We computed the slope MTF using our slope measurement as shown in figure 8. We see the magnitude peak of the slope MTF occurring at the second harmonic of the primary

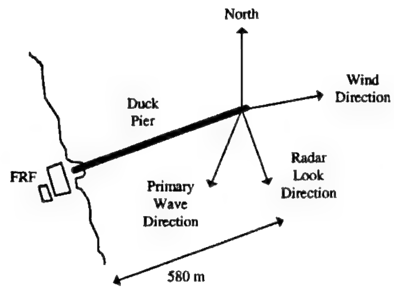
wave frequency, 3 dB up from the primary wave frequency peak. The strong coherence between slope and power leads us to believe there is a definite power-slope relation. We notice the slope MTF magnitude to be about an order lower than what linear wave theory predicts. The slope MTF phase of about 0° matches linear wave theorys phase prediction of 0°. Our new robust auto-regressive technique also shows the slope and power are nearly in phase. We believe sufficient non-linearites exist to invalidate the MTF's magnitude based on the linear wave theory for the conditions present during our measurements. We need slope measurements over a variety of different experimental conditions over the open ocean to make reasonable speculation as to the conditions that make the surface slope non-linearites invalidate the MTF's magnitude.

c.2) ***Auto-Regressive Analysis of Power-Slope Modulation***

Our autoregressive (AR) approach permits a new view of the modulation of the radar signal versus position on the wave [Salam, et al., 1992]. Using it we obtain the average radar return and average surface slope versus the phase of the long wave [Haimov, et al., 1993]. The distance from the crest for a given cycle is different from that for the other cycles. We convert this distance into phase for the specific cycle, and the radar signal and slope at that point are recorded as being at the correct phase. When this is complete for all cycles in the data, we average the signals for each phase. This method does not require that one treat the frequency components in the wave spectrum separately. The AR method also applies to all waves.

The AR approach can obtain frequencies from very short samples [Haimov and Moore, 1995]. We first find the lowest frequency present (within the filter width used). The period of this wave becomes the length of a short window. The AR technique uses this window on the first data segment to find the length of the cycle. The process repeats with the start of the window moved to the end of the first cycle, and so on, until the complete record has been treated.

Using AR we show in figure 9 the normalized waveheight, return power, and slope versus the long-wave phase. The asymmetry and non-sinusoidal shape of the long wave is shown clearly. We see the return power and surface slope have the same shape and nearly identical phase. From this result we observe the presence of significant tilt modulation as well as hydrodynamic effects. The AR predicts the same maximum power return at a



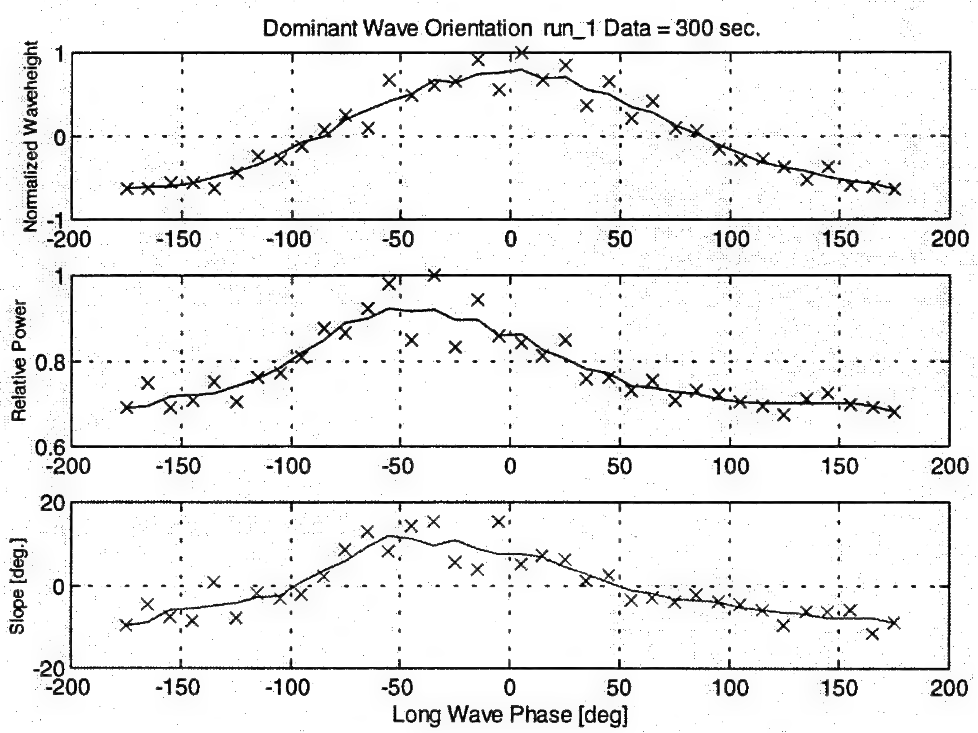
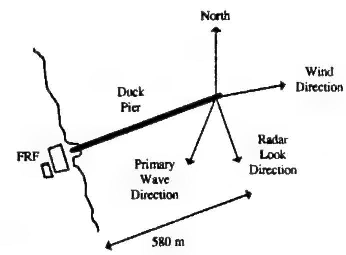


Figure 9. Auto-regressive analysis of VSG run_1.
data file run_1 collected on 12/09/95 for 5 min. Incidence angle is 61°. Wind Speed is 4.5 m/s. Wind Direction is 258°. Primary Wave Direction is 29°. Radar Look Direction is 160°. Polarization is VV.

long-wave phase of 50° as the wave height MTF shown in figure 4. The modulation of power and slope along the long wave is seen to occur nearly in phase as one would expect and to agree well with the slope MTF phase of about 0° shown in figure 8. By this result we show the importance and usefulness of the AR method and also the difficulty in interpreting the MTF's spectral approach.

The AR method provides us with the long-wave relations of the power and slope. By using both relations we can find the power versus slope relation. We plot the return power versus surface slope in the radar look direction in figure 10 with a linear fit shown by the solid line and the data points by the symbol x. We believe the deviations from the fitted line at the higher return powers may be contributed by hydrodynamic effects as well as by sea spikes and noise.



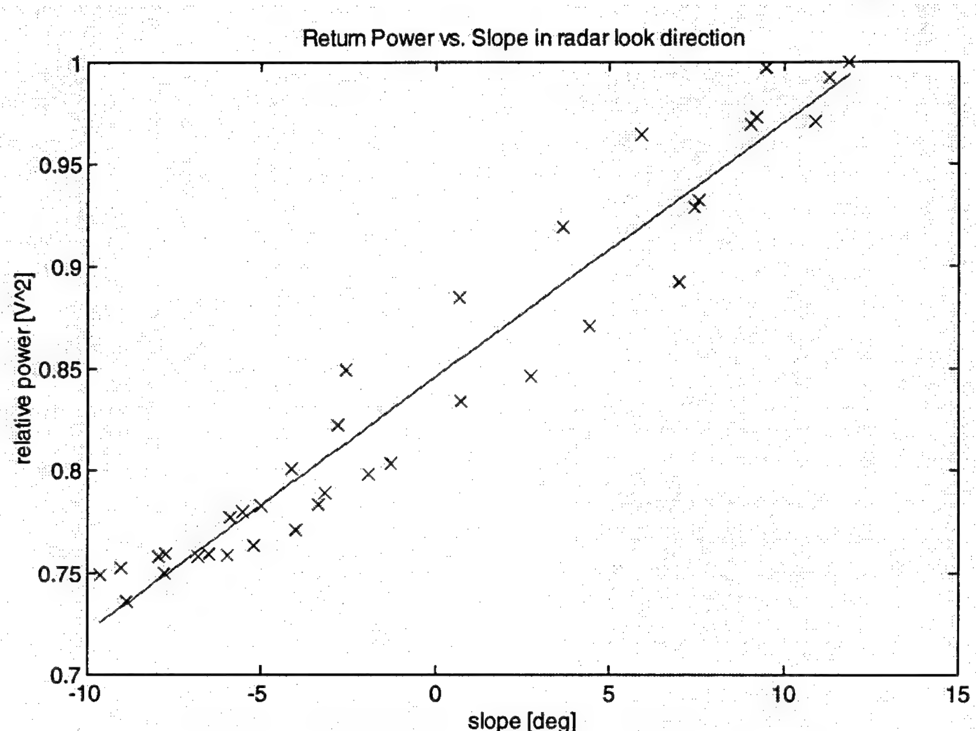


Figure 10. Power-slope modulation using new AR method.
data file run_1 collected on 12/09/95 for 5 min. Incidence angle is 61°. Wind Speed is 4.5 m/s. Wind Direction is 258°. Primary Wave Direction is 29°. Radar Look Direction is 160°. Polarization is VV.

We find the power of the AR method to analyze the individual long-wave cycles to be an extremely powerful tool. We are preparing a paper for submission to a journal highlighting the AR method and how the AR method can be applied to radar backscatter measurements of the ocean.

d) Sea Spikes at Moderate Angle of Incidence

d.1) *Sea Spikes at Ka Band from VSG*

We used a 6-dB moving-average threshold to determine sea spike occurrence. At Ka band for low wind speeds less than 5 m/s, we see only a few spike occurrences over a 20-min. period; these may all be due to the fading distribution of the radar signal. For wind speeds between 6 m/s to 9 m/s, the sea spike occurrences are still within distribution expected value. However for wind speeds of 6 m/s to 9 m/s, the majority of occurrences are likely spike events with durations on the order of 0.1 s.

d.2) *Sea Spikes at Ku Band*

Using the same 6-dB moving-average threshold we determined Ku-band sea spikes. Over the same 20-min. data period as the VSG for wind speeds less than 5 m/s we see only a few spike occurrences, and again they may all be due to the distribution of the radar signal. However for the same 20-min. data period as the VSG at wind speeds of 6 m/s to 9 m/s, we see about twice as many spike occurrences than would be statistically expected. More spikes at Ku band than Ka band may be due to the larger footprint at Ku band suggesting small surface phenomena are causing strong radar returns for this data run.

d.3) *Sea Spike Summary*

From both Ku band and Ka band at wind speeds less than 5 m/s we found very few spikes, on the order of 1 per 20 long wave cycles. At wind speeds of 6 m/s to 9 m/s from both Ku band and Ka band we found sea spikes with durations on the order of 0.1 s; also for this case there is reason to speculate that the spike phenomena may be due to small surface area effects since the Ku-band system has a large footprint and saw more spikes.

e) Unusual Results

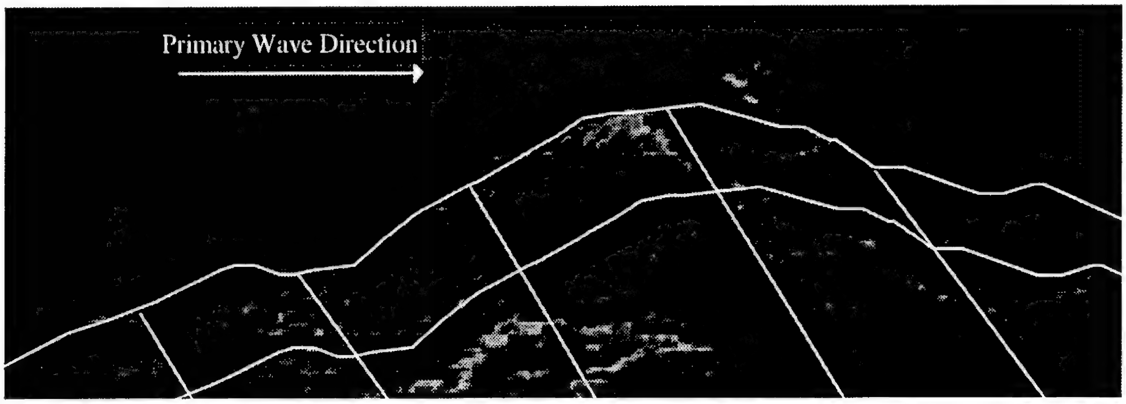


Figure 11. Photo of a wave with AR wave overlaid.

On 12/10/95 we made measurements of a wave train with several high-energy frequency components. We overlaid a rough not-to-scale AR reconstruction of a wave over a photograph of a wave from 12/10/95, as shown in figure 11. Spray and bubbles are visible on the back face of the wave in large quantities. The AR wave reconstruction shows clearly the multiple frequencies present in the long ocean wave.

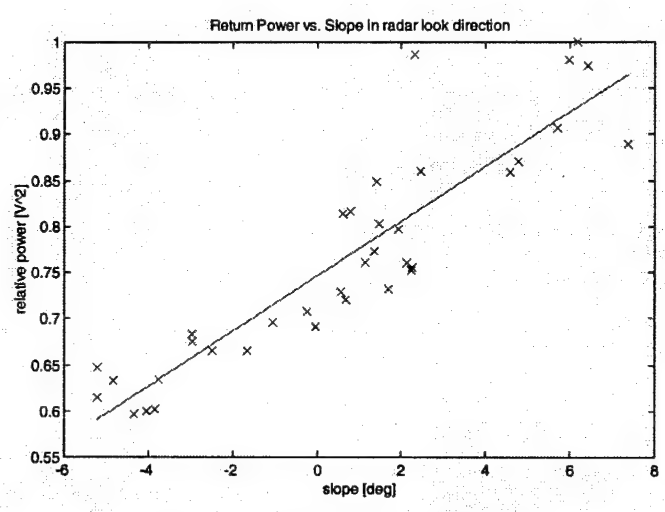


Figure 12. Power-slope modulation.
data file run_8 collected on 12/10/95 for 2.5 min. Incidence angle is 61°.
Wind Speed is 8.7 m/s. Wind Direction is 311°. Primary Wave Direction is 18°.
Radar Look Direction is 160°. Polarization is VV.

Interestingly, we see a similar power-slope trend from the multiple frequency wave train shown in figure 12 as we did from runs on 12/9/95 shown in figure 10.

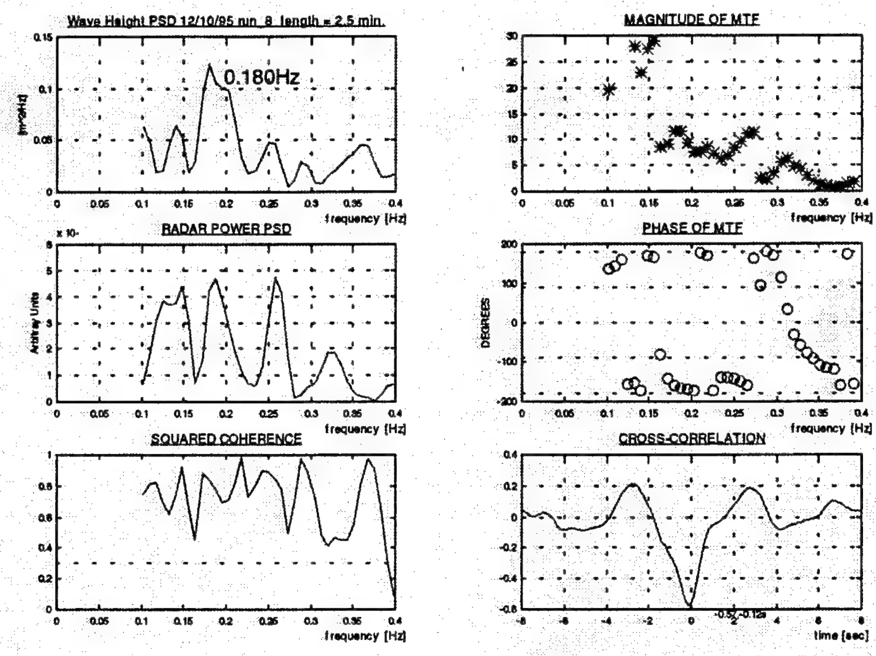


Figure 13. VSG waveheight MTF.
data file run_8 collected on 12/10/95 for 2.5 min. Incidence angle is 61°. Wind Speed is 8.7 m/s. Wind Direction is 311°. Primary Wave Direction is 18°. Radar Look Direction is 160°. Polarization is VV.

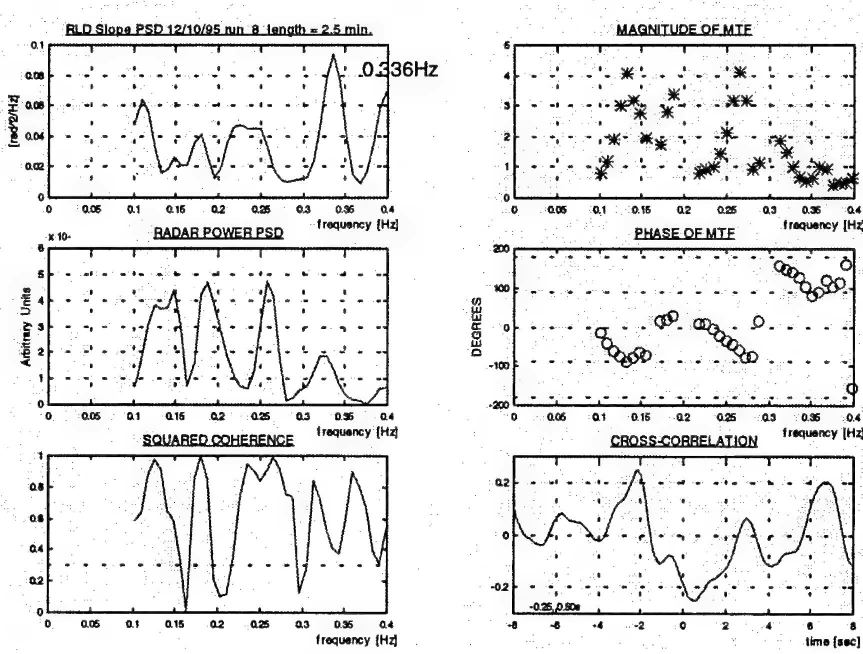


Figure 14. VSG slope MTF.
data file run_8 collected on 12/10/95 for 2.5 min. Incidence angle is 61°. Wind Speed is 8.7 m/s. Wind Direction is 311°. Primary Wave Direction is 18°. Radar Look Direction is 160°. Polarization is VV.

Several maxima exist in the waveheight power spectral density (PSD) with the maximum peak occurring at 0.18 Hz; the corresponding radar signal PSD shows three peaks with nearly the same energy shown in figure 13. The slope PSD shows the maximum slope energy at 0.34 Hz, approximately the 2nd harmonic of the dominant energy peak of the waveheight PSD of 0.18 Hz shown in figure 14. Note the coherence function is biased somewhat due to the short data sample of 2.5 min. The VSG measured a maxima in the slope spectra corresponding to nearly each of the peaks in the waveheight spectra.

This unusual run illustrates the VSG's usefulness in analyzing complicated situations. The wave-direction-finder capability of the VSG successfully found the primary wave direction to be 18°, which is within 7° of the FRF visual measurement. The measured surface slope combined with the new AR technique shows a strong power-slope relation even for the complicated scene. We believe the VSG to be an important tool in understanding situations that would normally be difficult to understand without direct surface slope measurements.

III. Future Work

Both the VSG and C-/Ku-band systems have the capacity to measure simultaneously the ranges to the surface and the radar signal strength. Therefore the combined VSG—C-/Ku-band system allows comprehensive study of radar sea response and its relation to ocean waves. Our Duck Pier experiment successfully proves the concept of our ocean measuring system.

We need to move forward now to our planned open sea experiment at an off-shore oil platform in the Gulf of Mexico. In this we have been cooperating with JHU-APL and UWASH-APL scientists. The latter have identified a production platform, Brazos-19. This platform has two structures connected by a bridge. For one experiment, the VSG would be located on the bridge, looking vertically, and the other scatterometers would be far enough away so that they could observe the same spot on the surface as the VSG, but at, say, 45° angles of incidence. For Ka-band scattering studies, the VSG will be operated off vertical, with other scatterometers viewing the same spot.

We have found several interesting results from our Duck Pier experiment. Our new AR technique used in analysis of the Duck Pier experiment is a powerful approach that permits a new view of the modulation of the radar signal versus position on the long wave. The VSG slope measurements allow measurement of the wave direction that may prove to be a powerful tool for oceanographers. The VSG mean-square slope shows dependence to the wind speed. In the immediate future, we are preparing several papers based on the Duck Pier experiment for publication in refereed journals.

IV. Results Summary

Our experiment at Duck Pier allowed us to successfully determine the significant waveheight, wave period, wind speed, wave direction, slope-power modulation, and the MTF.

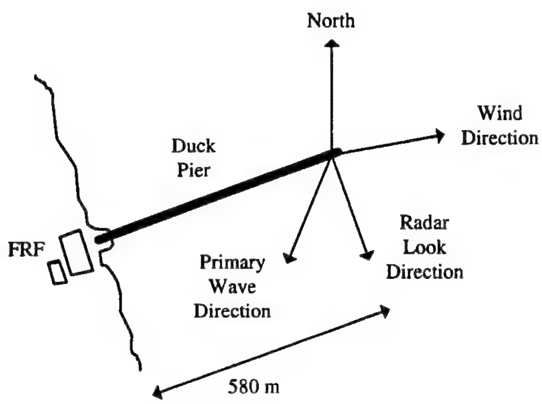


Figure 15. Duck Pier scene.
Data record on 12/9/95 from 4:00 to 7:00 p.m. (east).

Table 1. VSG and FRF Measurement Comparison.

	VSG Ka-band Measurement	*Field Research Facility Measurement*	*Comparison of VSG - FRF difference*
Waveheight	**0.84 m**	**0.89 m**	**6 %**
Wave Period	**8.80 sec.**	**8.66 sec.**	**2 %**
Wind Speed	**5.0 m/s**	**4.9 m/s**	**2 %**

Data collected on 12/9/95 from 4:00 - 7:00 p.m. (east).
Gauge 625 used for FRF wave period and waveheight.
Gauge 3932 used for FRF wind Speed.

Our measurements of significant waveheight, wave period, and wind speed show strong agreement to FRF's nearby comparable measurements summarized in Table 1. Figure 15 shows the Duck Pier experimental scene for the results in table 1. Our measurements are taken on the *back face* of the primary wave. The primary wave direction during the entire experiment occurred about midway between downwave and crosswave (toward shore).

We determine the primary wave direction from the two orthogonal components of the surface vector slope. We show in figure 16 the wave direction of 18° found from the VSG slope measurement. We made the VSG slope measurements of run_8.1-3 on 12/10/95 from 9:35 - 10:05 a.m. (EST). FRF staff made their daily visual measurement of 25° for the primary wave direction at the end of Duck Pier at 10:28 a.m. (EST). Approximately 450 m away, FRF gauge 3111 (an array of 15 pressure gauges) found the primary wave direction to be 30° based on a 4-hour average of measurements.

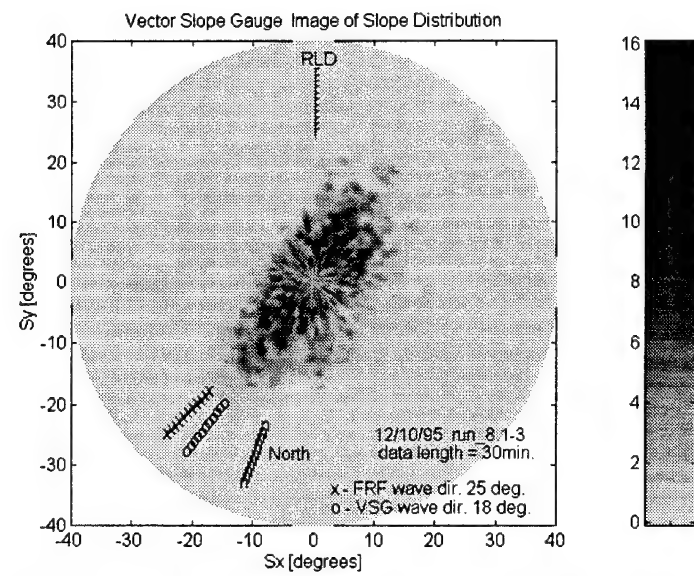


Figure 16. Primary-wave direction determined by VSG slopes. **data file run_8 collected on 12/10/95 for 32 min. Incidence angle is 61°. Wind Speed is 8.7 m/s. Wind Direction is 311°. Primary Wave Direction is 18°. Radar Look Direction is 160°. Polarization is VV.**

Our wave-direction measurements show strong agreement to FRF's wave direction measurements over the entire day of 12/10/95. Interestingly on 12/09/95, gauge 3111 measured a distinctly different wave direction of 106° compared to our logbook visual measurement of 25° and the VSG measurement of 29°. We contacted Dr. Chuck Long, the FRF staff member in charge of the wave directional spectra measurements, and asked him about the ambiguity. Dr. Long said that the pressure gauges near the bottom of the ocean may have measured the correct wave direction for its underwater location; however, he also said it was not unusual for low winds (< 6 m/s) and low significant waveheights (0.5 m to 1.0 m) on the surface to be missed by the gauge if a recent storm out in the open ocean caused high energy from a different direction to be present at the underwater gauge. Our measurements on 12/9/95 were at low wind speeds and low significant waveheights, we believe our measurement as well as the visual observation are correct and gauge 3111 measured an underwater phenomenon that was not a good indicator of the actual surface behavior.

Using our new AR technique, we see a trend in the power-slope relation shown in figure 17. We fit a straight line to the data points (symbol x on plot). We believe the data point spread about the fit at higher power may be due, at least in part, to hydrodynamic modulation.

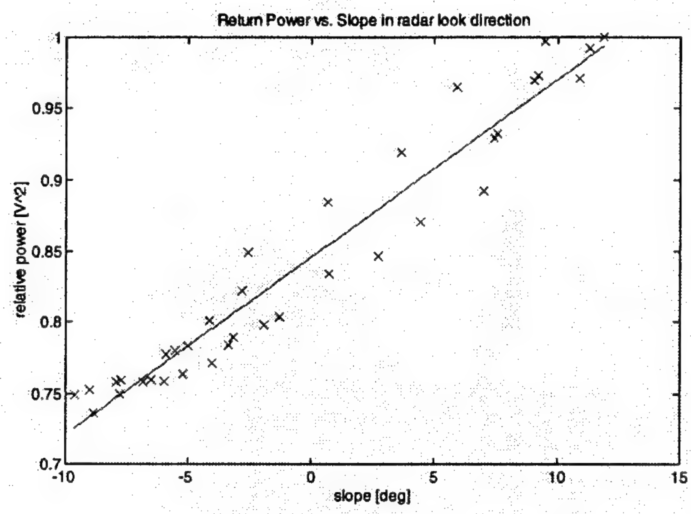


Figure 17. Power-slope modulation.
data file run_1 collected on 12/09/95 for 5 min. Incidence angle is 61°. Wind Speed is 4.5 m/s.Wind Direction is 258°. Primary Wave Direction is 29°. Radar Look Direction is 160°. Polarization is VV.

The waveheight MTF from 12/9/95 measurements interestingly show the phase of the maximum modulation to be near the long-wave crest, off by 30° for the VSG and 50° for the Ku-band scatterometer. The slope MTF shows the slope and power to be in phase as expected; however, the magnitude of the slope MTF is an order lower than what is expected using linear wave theory. We believe the linear assumptions in the MTF do not hold for our measurements at Duck Pier since our AR technique (that is not bound by the same assumptions) shows the same phase as the MTF but the slope MTF magnitude differs by over an order of magnitude. The interesting MTF results from 12/10/95 show the VSG's robust slope-measuring capability even in the presence of multiple wave trains.

Our Duck Pier experiment has verified the concept of the VSG as a slope-measuring instrument. Our measurements agree with similar measurements made by FRF. As a result of our experiment, we believe a new open-ocean experiment is warranted to investigate in depth the full potential of the Vector Slope Gauge as an ocean-measuring device.

V. Conclusion

Our Duck Pier experimental results prove the concept of the Vector Slope Gauge. We have good agreement with the Field Research Facility measurements of waveheight, wave period, wind speed, and wave direction. We see a trend between our radar signal and surface slope measurements that may be fitted reasonably well by a straight line or exponential curve. Dr. Bruce Gotwols and Dr. Don Thompson at JHU-APL seemed excited by our preliminary results of power-slope modulation. We sent a sample of our data to them at their request, and they are in the process of using our data in their model: $\sigma_o = C \cdot e^{(a_1 \cdot s_y + a_2 \cdot s_y^2)}$ where C is a constant, s_y is the slope in the radar look direction, and a_1 & a_2 are coefficients determined by their model [Gotwols and Thompson, 1994].

Since wave direction was midway between downwave and crosswave, the usual spectral approach is difficult to interpret; therefore, we applied our new AR technique to our data. Our AR results and slope MTF results show the ocean surface slope and radar signal to be nearly in phase for our Duck Pier measurements. We demonstrated the power of the AR technique by finding some clue to the nature of the complex wave system measured on 12/10/95.

We did not distinguish any sizable number of sea spikes for runs where the wind speed varied from 4 m/s to 5 m/s, meaning all spikes we did find may be accountable from the tail of the usual fading distribution. For runs with the wind speed in the range of 6 m/s to 9 m/s, we did find more sea spikes than would be accountable by the tail of the distribution alone, with spike durations on the order of 0.1 s. We presently are investigating in greater detail the sea spikes at our moderate angle of incidence of 61° and expect detailed results over the summer.

The VSG and its complementing scatterometers offer a new powerful means to study the interaction of ocean waves and radar signals. We have demonstrated the slope-measuring

concept of the VSG at Duck Pier. Also, we have shown the VSG to be operational as an ocean directional spectrum analyzer. Our complementing Ku-band scatterometer worked well at Duck Pier and the Ku-band measurements were nearly identical to the VSG. We applied our new AR technique to our measurements of waveheight, radar signal strength, and slope. Viewing the AR results from Duck Pier, the ocean long-wave non-linearitites are clearly seen. Our AR technique, combined with our measurements of radar signal strength, waveheight, and vector slope, should allow resolution of significant questions that remain about the basis for oceanic modulation of the radar backscatter. To this end, we need to conduct an open-sea experiment with other participants in the future.

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We performed a successful experiment to verify performance of the revised Vector Slope Gauge (VSG) and Ku-band scatterometer. We made measurements of the two orthogonal components of the ocean surface slope at Duck Pier the second week of December 1995 with the VSG. The radar backscatter measurements at Ka band (VSG) and Ku band were of the same area on the ocean surface. Using the VSG-measured slopes, we determine primary wave direction, power-slope modulation, and an estimate of the wind speed. Our measurements show strong agreement to the US Army Field Research Facility's (FRF) comparable measurements of waveheight, wave period, wind speed, and wave direction. Our powerful new Autoregressive (AR) technique examines individual cycles of the primary wave and allows us to see the non-linearities associated with each wave cycle instead of the traditional frequency dissecting when using the modulation transfer function (MTF). The AR method does not have any restriction to the primary wave direction. We illustrate the usefulness of the VSG by applying the AR technique to the VSG slope measurement. We are excited by the Duck Pier results and look forward to using the proven VSG in the full open-ocean environment.

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